Effect of Glue-line Flexibility on Cleavage Fracture Toughness of Wood-Epoxy Resin Bond System

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Masahiro TAKATANI* and Hikaru SASAKI*

Abstract——The paper concerns with effect of the mechanical properties of glue-line on the cleavage fracture toughness of wood-epoxy resin bond systems. Tensile stress-strain relations of the resin films flexibilized with polysulfide in various grades were tested at a range of head speed 0.09 mm/min to 180 mm/min and temperature 20°C to 60°C. Resins containing 20 to 40 parts per hundred of resin (phr) behaved like elasto-plastic material and that of 60 phr like rubber.

Numerical analysis of stress distribution in cleavage fracture toughness test specimens of wood-flexibilized epoxy resin bond system was made by using the values of mechanical properties of resin films obtained above. Less stress concentration was found on the tip of a crack in thicker and more flexible glue-line. Higher stress concentration was found on thinner and more rigid glue-line and on lower density adherend.

Test results on cleavage fracture toughness G_{IC} of wood-epoxy resin bond specimens showed clearly that increasing flexibility and thickness of glue-line could effectively improve cleavage fracture toughness of wood-glue bond system.

Introduction

Versatility of mechanical properties of epoxy resin with mixing flexibilizer involves possibility to improve the performance of wood glue joints subjected to cleavage (sometimes impact) load such as corner joints of furnitures and notches of glued laminated beams.

Fracture toughness (G_{IC}) of cleavage (opening) mode of wood-epoxy resin bond system was studied so far by Sasaki et al.[1], Sasaki[2], and Komatsu et al.[3,4]. They suggested in their paper that the flexibility and thickness of glue-line were the most important factor affecting the fracture toughness of glue-line. This is rather natural because the mechanical properties and thickness of glue-line are concerned much with stress distribution around the tip of crack in the glue-line and with the possible maximum value, and these have a direct connection with the other definition of fracture toughness K_{IC} which is mutually conversible with G_{IC}.

Efforts have however little been made to clarify the relations among the elasto-plastic behavior of glue-line, adhesive and cohesive forces in wood-glue bond system,

* Division of Composite Wood.

stress and strain distribution in the system, and the energy required to propagate crack by unit area (fracture toughness G_{IC}). These are too complicated and difficult problems to solve easily.

This paper is the first step to approach the above subject, and consist of three items, namely, tensile tests of adhessive film specimens, numerical stress analysis of cleavage test specimens and cleavage fracture toughness test of wood-epoxy resin bond specimen.

Though the combination and discussion among these three items are not good enough in this paper, an aspect of cleavage farcture of wood-epoxy resin bond system shown here could be useful information to the future advance in this research field.

One part of the resin film tensile tests of this paper were carried out at the Division of Forest Products (now the Division of Building Research), CSIRO, Australia by the second author Special acknowledgements are due to the staffs concerned of the Conversion Section and the Engineering Section, DFP, CSIRO, and to Mrs. Katsuyama for her helpful drawings.

1 Mechanical Properties of Epoxy Resin Film

1·1 Materials and Experimental Procedures

1·1·1 *Adhesives and Flexibilizers*

The basic material tested was a commercial epoxy resin of bisphenol A type of 180–190 WPE*1 mixed with 20% dibutyl phthalate (CIBA Ltd., Araldite CY230). This resin was flexibilized to four different levels by mixing a commercial flexibilizer of polysulfide (Thiokol LP-3). Polysulfide was added to the resin in 0, 20, 40, and 60 phr*2 levels. (in this paper these mixed resins are denoted with symbols of EP-0, EP-20, EP-40 and EP-60, respectively). Catalyzer DETA (diethylene triamine) of 11 phr was added to these mixed resins before moulding.

1·1·2 *Specimen Preparation*

Necked-down type film tensile specimens (Fig. 2(a)) were prepared by almost similar method as Sympson et al.[5,6]. The method of casting resin film specimens is illustrated Fig. 1.

Silicone rubber resin mixed with the catalyzer was poured on a steel model of specimen coated with release agent. After curing the silicone rubber resin was removed from the male mold.

After release agent was coated thinly on the silicone rubber-made mold, epoxy resin mixed was poured into the specimen impression of the mold. An acrylic resin plate coated with the release agent was lowered onto the mold to squeeze out the excessive resin and to force out all air bubbles. A weight was then placed on the acrylic

*1 WPE: Weight per epoxy equivalent.
*2 phr: Parts per hundred of resin by weight.

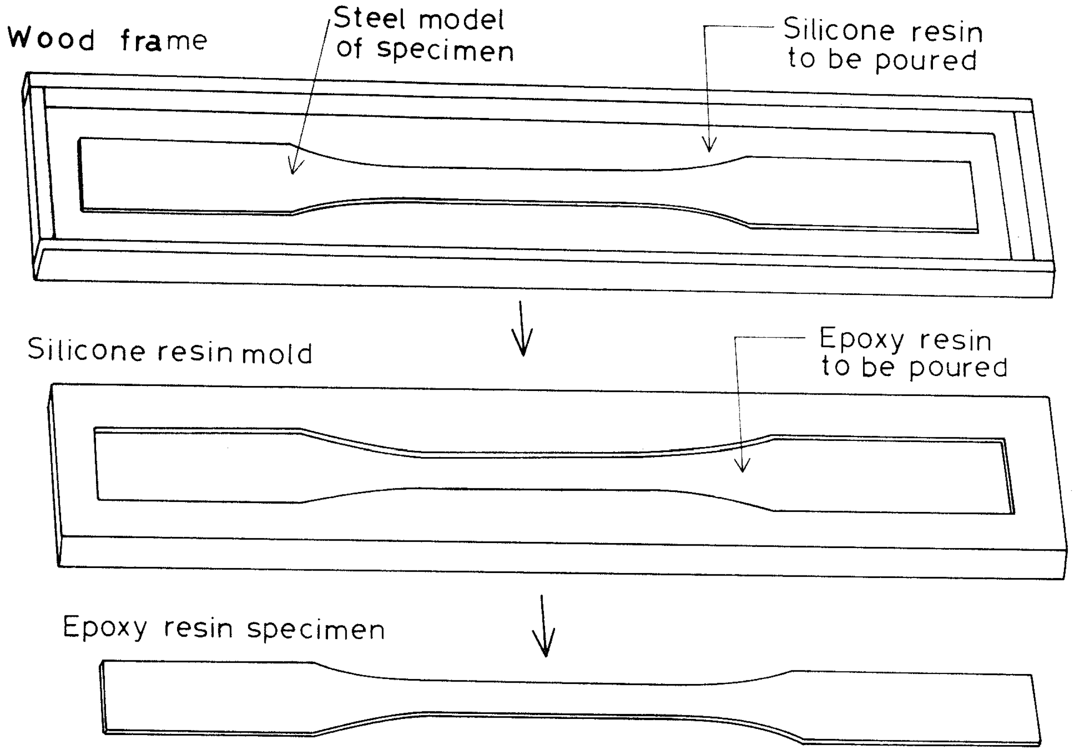


Fig. 1. Molding of epoxy film specimen.

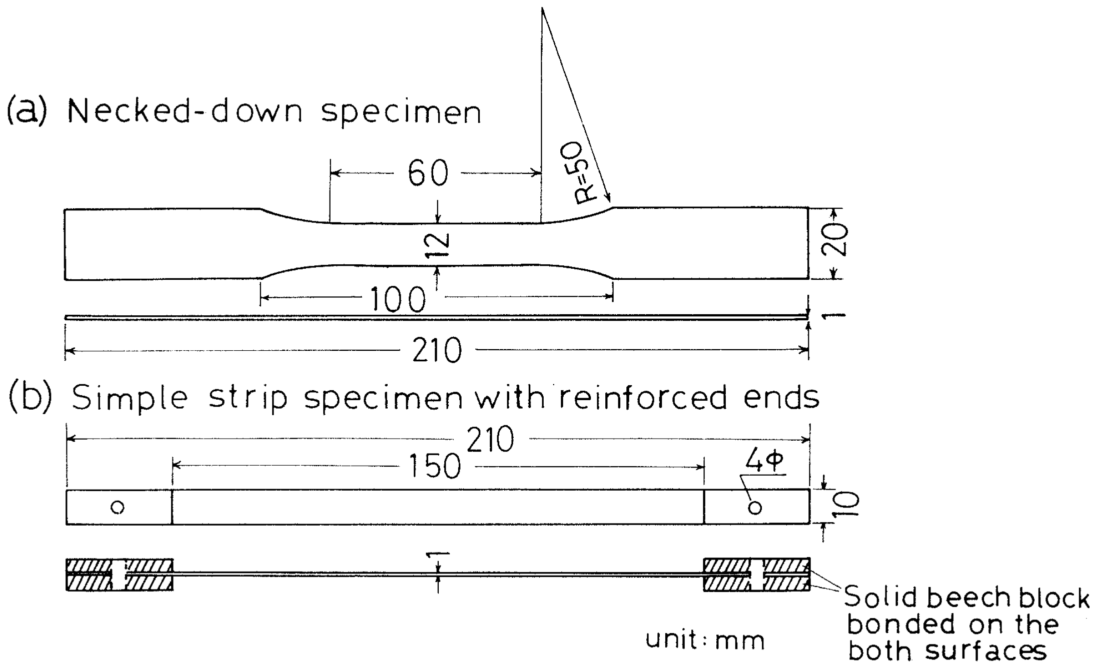


Fig. 2. Specimen for tensile test of epoxy resin film.

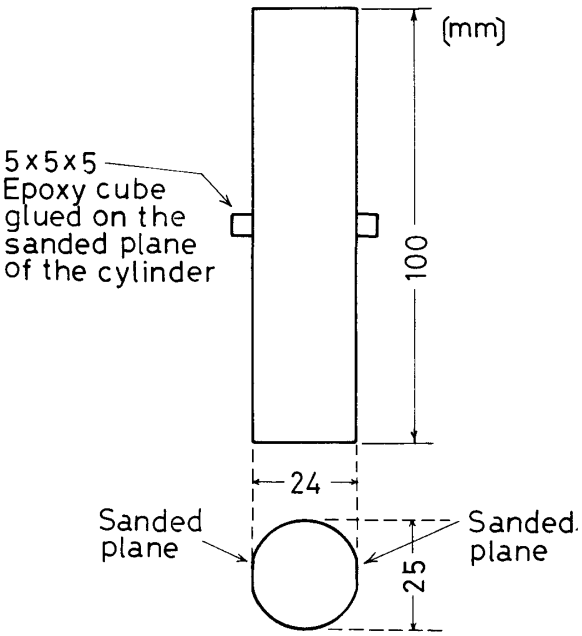


Fig. 3. Compression specimen of epoxy bulk for measuring Poisson's ratio.

resin plate. The resin was cured at 20°C, 65% RH for 24 hr, then the cured resin was removed from the mold and the squeeze-out of the resin was cut off with a razor blade. The final geometry of necked-down specimen is shown in Fig. 2(a).

In the same procedures, simple strip type specimens (Fig. 2(b)) were molded for tests at temperatures higher than room temperature because the temperature dependency of extensometer forced to take another way to measure strain. Simple stript specimens were reinforced with solid beech blocks at the both ends. The shape and dimension of the simple stript specimens were shown in Fig. 2(b).

Epoxy resin bulk specimens for measurements of Poisson's ratio were prepared in the following procedure; The vinyl chloride tube with a bottom was coated with release agent and used as a mold for the specimen. Epoxy resin mixed were poured into the mold. As the volume of mold was large, the resin became hoter with the reaction heats and finally, bubbles came out and cured resin is porous. Therefore the resins were put into a freezing chamber of −5°C to keep the reaction rate slow. After 24 hours, homogeneous resin bulk specimen were cured and removed from the mold. The upper and lower end surface were sanded to make flat and parallel. As shown in Fig. 3 two opposite edges were sanded and small cube of epoxy resin were bonded there to clamp a lateral extensometer.

1·1·3 *Measurement of Stress-Strain Relations*

a) Measurement at room temperature

All experiments were carried out at the conditioned room with 20°C, 65% RH.

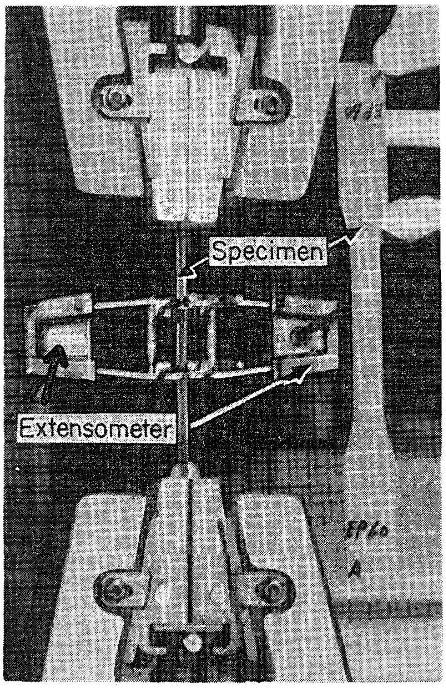


Photo. 1. Tension test of epoxy resin film specimen at room temperature. (Necked-down specimen)

The necked-down specimen was clamped with the tension grips to Instron Material Testing Machine Model K, and a pair of mount type electric extensometers was attached to middle part of the specimen (Photo. 1), and the stress-strain curve was recorded until the specimen fails. During the measurement, strain often exceeded the capacity of extensometer (10%), and the extensometers were quickly reset.

The variables taken in this test were strain rate (0.09–180%/min) and flexibilizer content (0–60 phr).

b) Measurement at different temperatures

For the practice in furniture and wood construction, the influence of temperature up to 60°C was examined. As the electric extensometer had different sensitivities at different temperatures and was not convenient for the temperature dependency tests, another device to measure strains was needed.

Simple stript specimens shown in Fig. 2(b) were used for this purpose. Tensile load was given in a thermo-controlled box by means of the method shown in Fig. 4. Tensile strain was obtained from the displacement of cross head by subtracting total displacement of the loading system itself such as looseness of pin connection at the both ends of specimen, deformation of the attachments and the load cell—these values were determined in the preliminary test.

c) Determination of Young's Modulus

As stress-strain curves thus obtained were non-linear in general, determination of

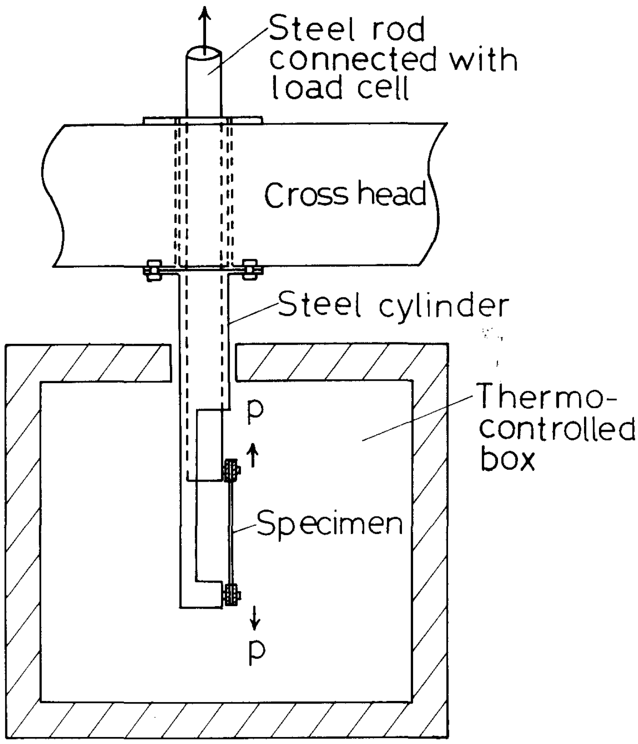


Fig. 4. Tension test device.

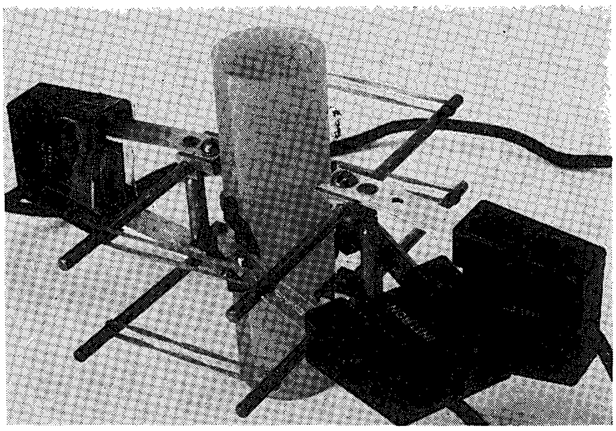


Photo. 2. Extensometers set on compression test specimen of epoxy resin bulk.

modulus of elasticity was made on convenient definition. The slope of a secant line from the origin to the point at 1 percent strain was used for calculating Young's modulus of the resin film.

d) Measurement of Poisson's Ratio

As shown in photo. 2, a pair of electric extensometers for the measurement of longitudinal strain and an extensometer for the measurement of lateral strain were set on the specimen simultaneously, and then longitudinal and lateral strains were recorded on X- and Y- axis of a pen-reocrder, respectively. Loads were given by Instron material testing machine model K with head speeds 2 mm/min at 20°C.

Poisson's ratio of the specimens were expressed as the average ratio of longitudinal strains to lateral strains at more than ten load levels with optional interval.

1·2 Results and Discussion

1·2·1 *Influences of flexibilizer content and strain rate on stress-strain relations at room temperature*

As shown in supplemental figures 1–5 described at the end of this paper, the stress-strain curves of epoxy-polysulfide resin were greatly influenced by both of amount of polysulfide mixed and strain rate.

Examples of raw stress-strain curves observed for EP-0 are plotted in supplemental Fig. 1. Those for the other resin formulations are omitted. Supplemental Fig. 2–5 are

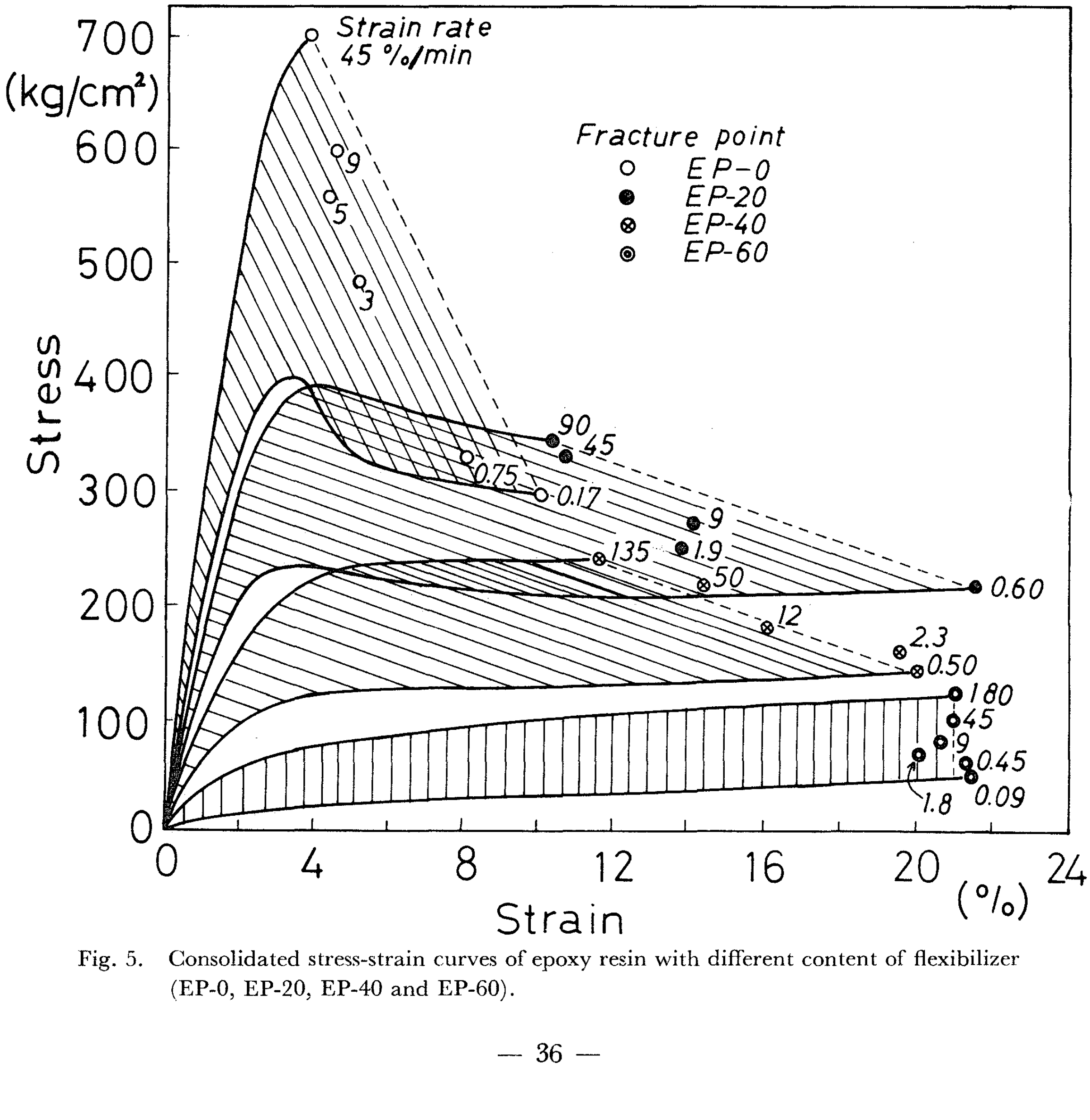


Fig. 5. Consolidated stress-strain curves of epoxy resin with different content of flexibilizer (EP-0, EP-20, EP-40 and EP-60).

the abbreviation of the individual data for EP-0, EP-20, EP-40 and EP-60, respectively. Each curve in these figures expresses the average of 3 to 7 measureemnts. These curves are consolidated and shown in Fig. 5. From this figure it can be seen that in most case the initial slope and the maximum stress increase and the maximum strain decreases with increasing test speed and/or with decreasing polysulfide content.

The yielding point is observed on the stress-strain curves of the unflexibilized resins (EP-0) at lower test speed, and after passing this point the stress decreases while the strain increases.

The yielding point is also found on EP-20. The stress-strain behavior of resin films of EP-20 and EP-40 is in general of elasto-plasticity, and that of EP-60 is greatly

Table 1. Formulations and tensile stress-strain parameter for film specimens of flexibilized epoxy resin.

Symbol	Flexibilizer added (phr[1])	Test speed in real strain rate (%/min)	Number of specimen tested	Modulus of elasticity at 1% strain ($\times 10^3$kg/cm^2)	Maximum stress[2] (kg/cm^2)	Maximum strain at failure (%)	Work to failure[3] $\left(\frac{\text{kg·cm}}{\text{cm}^3}\right)$	Existence of yielding point[4]
EP-0	0	45	7	32.7	690	3.50	15.9	Not exist
		9.0	7	28.2	595	4.15	18.0	Exist
		5.0	7	27.2	563	4.05	16.4	//
		3.0	7	24.7	505	4.95	19.1	//
		0.95	7	22.4	428	8.00	26.8	//
		0.5	5	21.0	398	10.1	30.8	//
EP-20	20	90	7	18.0	388	10.2	33.7	//
		45	7	17.1	375	10.4	33.0	//
		9.0	7	15.4	317	14.1	38.2	//
		1.9	7	14.7	278	13.6	32.8	//
		0.6	5	12.1	231	21.5	44.0	//
EP-40	40	135	7	9.63	238	11.4	23,1	//
		50	7	8.80	208	14.3	26.4	//
		12	7	7.38	184	16.0	24.6	Not exist
		2.3	7	6.50	159	19.3	25.6	//
		0.5	5	6.05	146	20.1	25.0	//
EP-60	60	180	7	3.32	123	21.0	21.0	//
		45	7	2.82	95.5	21.0	15.2	//
		9.0	7	1.78	77.5	20.8	11.4	//
		1.8	7	1.42	65.7	20.2	9.29	//
		0.45	5	1.01	57.5	21.3	7.97	//
		0.09	3	0.870	49.3	21.4	6.70	//

1) Part by weight per hundred parts of resin (with 11 phr hardener).
2) The stress calculated on the initial cross sectional area.
3) Area of the lower part of the stress-strain curve.
4) The point on the stress-strain curve where stress no longer increases with strain.

non-linear even at the initial part of the curves.

It is of interest to compare these curves with some stress-strain parameters. Table 1 shows the stress-strain parameters of the typical curves including modulus of elasticity, maximum stress, maximum strain at failure, work to failure, and existance of yielding point. In general, the stress-strain parameters correspond well to the flexibilizer content, that is, the modulus of elasticity and the maximum stress decrease with increasing flexibilizer content, while the maximum strain at failure increases and the yielding point disappears.

On the other hand, in each flexibility level, the modulus of elasticity and the maximum stress is apparently decreases and the maximum strain at failure generally (except EP-60) increases with decreasing test speed.

The work to failure is not influenced by flexibilizer content so much as the above three parameters.

1·2·2 *Influences of temperature and strain rate on stress-strain relations of EP-***0** *resin film specimens*

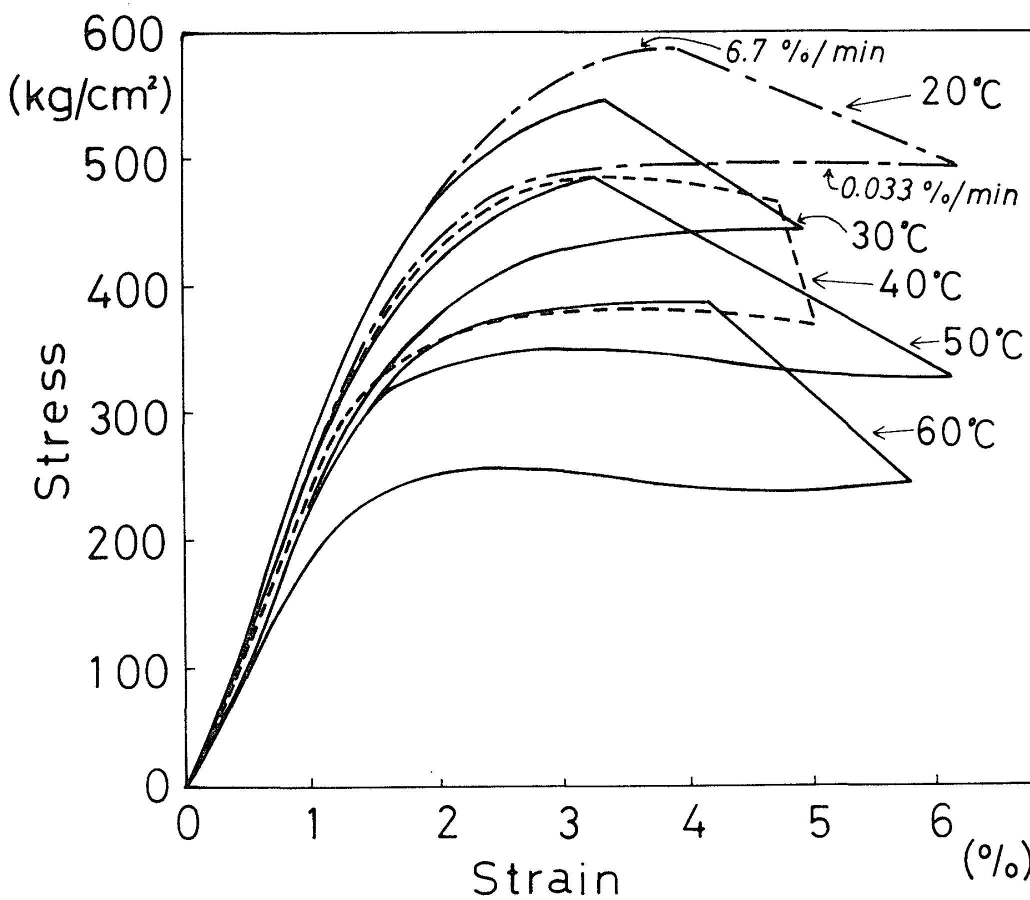


Fig. 6. Consolidated stress-strain curves of epoxy resin (EP-0) at a range of strain rate 0.033–6.7%/min and temperature 20–60°C.

Table 2. Tensile stress-strain parameter for film specimen of epoxy resin (EP-0).

Test temperature (°C)	Strain rate (%/min)	Modulus of elasticity at 1% strain ($\times 10^3 kg/cm^2$)	Maximum stress (kg/cm^2)	Maximum strain at failure (%)	Work to failure ($kg \cdot cm/cm^3$)
20	6. 7	28. 5	587	3. 75	14. 9
	0. 67	28. 1	550	3. 66	13. 8
	0. 33	28. 3	507	2. 75	8. 9
	0. 067	28. 3	525	5. 58	23. 5
	0. 033	27. 5	498	6. 05	25. 3
30	6. 7	28. 5	510	2. 48	7. 8
	0. 67	27. 6	515	4. 03	15. 0
	0. 33	23. 0	490	4. 11	13. 9
	0. 067	26. 8	459	2. 83	8. 7
	0. 033	22. 3	448	4. 90	16. 6
40	6. 7	25. 2	490	3. 13	9. 8
	0, 67	26. 6	483	4. 13	14. 4
	0. 33	27. 5	465	4. 75	17. 7
	0. 067	25. 8	405	3. 40	10. 1
	0. 033	24. 3	385	4. 40	13. 2
50	6. 7	26. 5	485	3. 13	9. 8
	0. 67	25. 3	428	3. 05	8. 9
	0. 33	25. 0	429	3. 55	10. 7
	0. 067	23. 7	373	5. 88	10. 2
	0. 033	23. 0	353	3. 70	18. 2
60	6. 7	23. 0	388	3. 25	8. 9
	0. 67	21. 6	350	4. 88	10. 3
	0. 33	20. 2	320	4. 98	10. 2
	0. 067	19. 6	276	4. 60	13. 0
	0. 033	19. 0	258	4. 81	13. 9

The stress-strain curves at 20°, 30°, 40°, 50° and 60°C of unflexibilized resin (EP-0) are shown in Supplemental figure 6–10 respectively. These curves are consolidated and shown in Fig. 6.

It is pointed out that the curves at 20°C in this figure are a little different from those of EP-0 in Fig. 5. It seems to be due to the difference in production lot between the two. Anyway, though flexibility of EP-0 resin increases with increasing test temperature, and decreasing strain rate, the effect is not so evident as that of flexibilizer (compare with Fig. 5).

Table 2 shows the stress-strain parameters of these curves. From this table it is seen that the modulus of elasticity and the maximum stress decrease with increasing tests temperature, and the maximum strains at failure and the works to failure of

Table 3. Poisson's ratio and Young's modulus obtained by compression test of flexibilized epoxy cylindrical bulk specimen at 20°C.

Symbol of formulation of epoxy resin	EP-0	EP-20	EP-40	EP-60
Poisson's ratio				
A*	0.445	0.461	0.487	0.497
B**	0.452	0.467	0.481	0.471
av.	0.449	0.464	0.484	0.489
Young's modulus ($\times 10^3$ kg/cm^2)	31.9	17.8	7.80	1.50

* Poisson's ratio A is the average of measurements under incremental load.
** Poisson's ratio B is the average of measurements under decremental load.

individual specimens are too widely scattered to show the tendency.

As to strain rate, the modulus of elasticity obviously tends to decrease with decreasing strain rate, and this tendency is commonly seen among these four temperatures. Temperature dependency like this is also observed on the maximum stress, which seems to decrease linearly with increasing tests temperature. It seems that the maximum stress and work to failure tend hardly to be influenced by strain rate with increasing tests temperature.

1·2·3 *Influences of flexibilizer content on Poisson's ratio at room temperature*

It is clear that Poisson's ratio increases with increasing the flexibilizer content

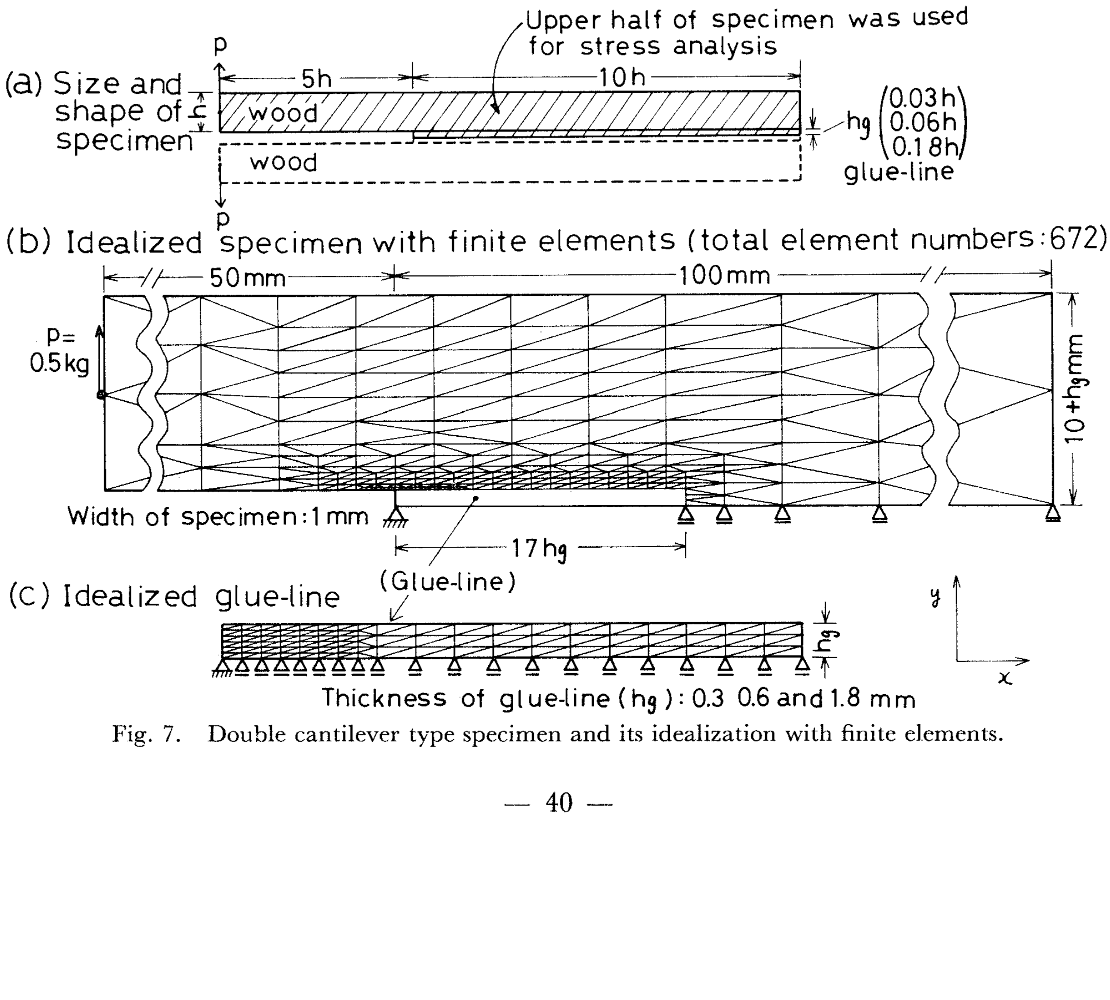


Fig. 7. Double cantilever type specimen and its idealization with finite elements.

as shown in Table 3. In particular, Poisson's ratio of EP-60 is approximately 0.5, which means keeping consistent volume of material under loading just like rubber.

2 Influence of Mechanical Properties of Glue-line on Cleavage Fracture Toughness of Wood-Epoxy Resin Bond Systems

2·1 Numerical analysis of stress distribution of cleavage fracture toughness specimen

2·1·1 *Method of numerical analysis*

Cleavage fracture toughness specimens used were a double cantilever type, and the shape and size of specimen was determined as shown in Fig. 7(a) on the basis of experimental results on solid wood by Poter[7] and results of numerical analysis carried out by the authors[8].

Fig. 7(b) shows the idealization of specimen with finite elements for the numerical analysis of stress distribution. In this case, as the specimen was symmetrical for the upper and lower side, the numerical analysis was carried out only on the upper half. Number of total elements are 672. Glue-line more than seventeen times glue-line thickness distant from the reentrant corner (imaginary crack tip) was omitted because it does not play important role on the stress distribution.

As shown in the figure, load of 0.5 kg per unit width of specimen (1 mm) was given on the left end of the specimen. This value was the average fracture loads of the specimens of the same sizes as used in the next section. The moduli of elasticity of wood and glue-line used in the calculations are showed in Table 4. In this table, moduli of elasticity of resin films observed in Section 1 at test speed 1–10 mm/min are used for the values of glue-line.

The computations were performed on a FACOM 230-75 computer in Kyoto University, and numerical analysis were carried out using a plane linear finite lement program with the unit partitioning.

Table 4. Mechanical properties of materials used for stress calculation by Finite Element Method.

Materials \ Properties		Modulus of elasticity E_x(kg/mm^2)	Modulus of elasticity E_y(kg/mm^2)	Modulus of rigidity G_{xy}(kg/mm^2)	Poisson's ratio $\mu_{\cancel{xy}\,yx}$
Wood[10]	Buna	1250	60	65	0.024
	Spruce	1140	47.5	68.5	0.025
	Balsa	390	6	14	0.009
	Ichiigashi	1650	95	90	0.032
Epoxy resin (EP-0)		225	225	88.2	0.445
Epoxy resin (EP-60)		16	16	5.3	0.498

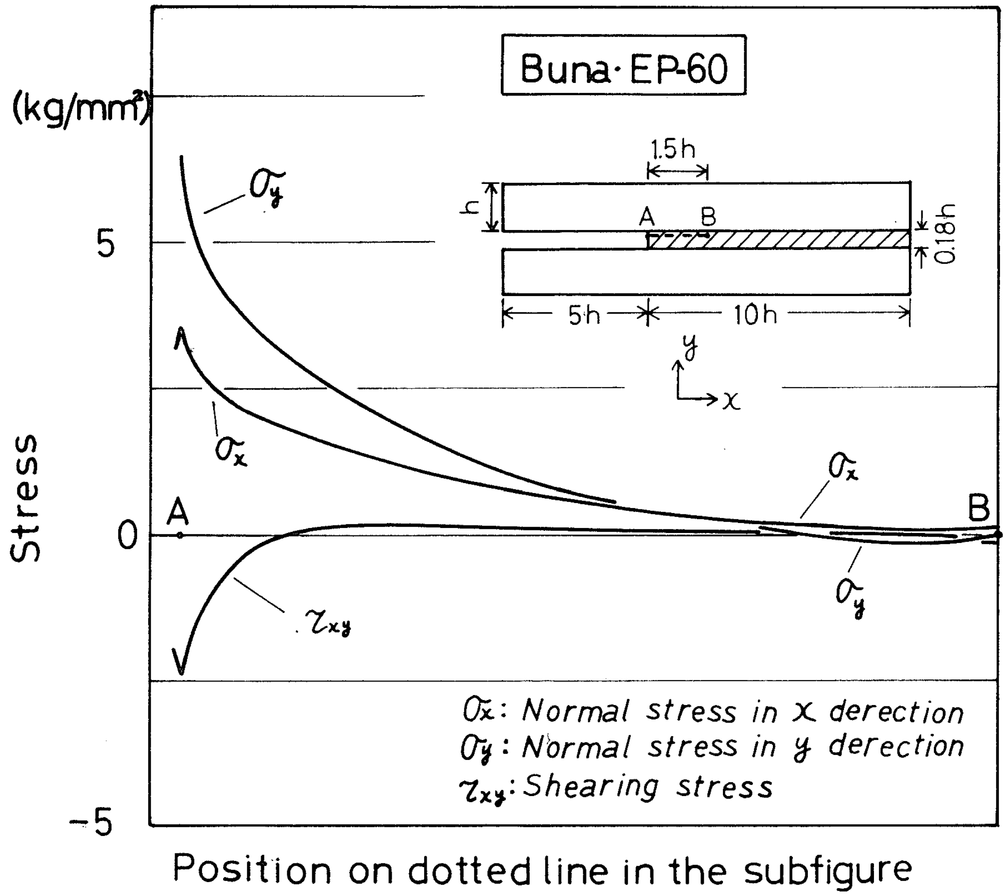


Fig. 8. Stress distributions in glue-line along glue-adherend interface AB.

2·1·2 *Result of numerical analysis*

Fig. 8 is an example of the distribution of stress component σ_x, σ_y and τ_{xy} in glue-line along a glue-adherend interface near the reentrant corner. This figure is an example of stress distribution calculated on a specimen with thick glue-line of highly flexibilized adhesive EP-60. It is not sufficiently obvious that which one or what kind of combination of the stress components are most concerned with the cleavage fracture.

The maximum principal stress

$$\sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}}$$

near the reentrant corner was taken as an index of the stress concentration, and compared. The results are shown in Fig. 9. As shown in the figure, σ_1 is greatly varied with kinds of adherend, the flexibility of glue-line and the thickness of glue-line. It is apparent from the figure that principal stress near the reentrant corner grows greater as glue-line is thinner and more rigid, and also adherend is lighter and more flexible. Accordingly, it is supposed that wood-adhesive bond system with flexible, thick glue-

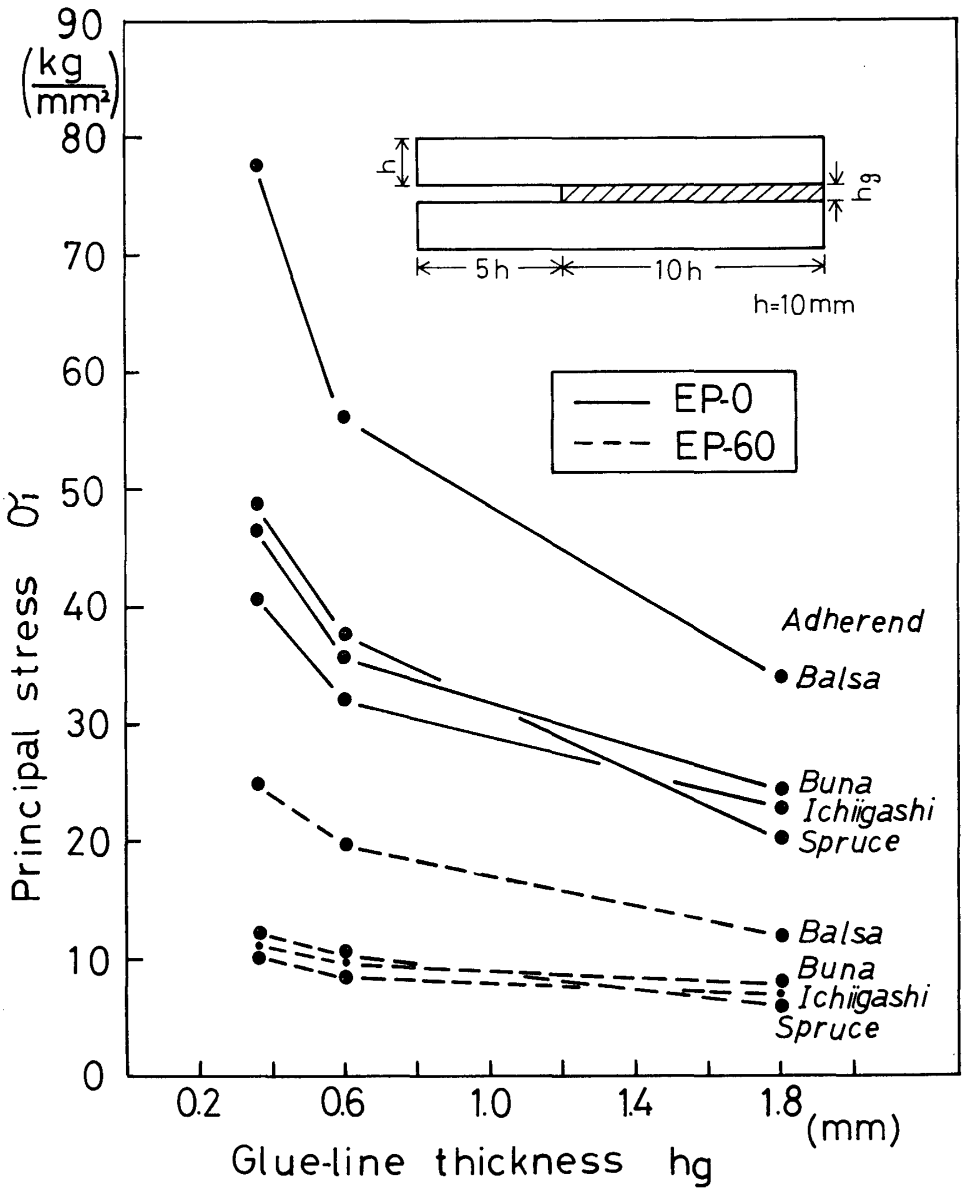


Fig. 9. Principal stress σ_1 at the reentrant corner of specimen as function of thickness of glue-line with parameter of species of adherend and flexibility of glue-line.

line and rigid adherend brings greater thoughness on the fracture in opening mode.

On the other hand, the values of stress in Fig. 8 and Fig. 9 are considerably greater than the lateral strength of wood and the tensile strength perpendicular to wood-glue interface.

Non-linear stress analysis is needed to remove this contradiction. In linear analysis, all stress components at any notch corners are infinity, so the above contradiction is rather natural. Though the non-linear analysis is under consideration, the results shown in Fig. 9 are thought to be still usefull to give a rough comparison of stress concentration which correspond to the order in brittleness of the specimens.

2·2 Measurement of cleavage fracture toughness G_{IC} of wood-epoxy resin bond system

2·2·1 *Specimens*

Specimens for cleavage fracture toughness test were prepared in the same shape and sizes as those used for the stress analysis in Section 2.

Adherends used are Taiwan hinoki (*Chamaecyparis formosensis Matsum*) and the sapwood of Buna (*Fagus crenata* BLUME), and with the average annual ring widths of 0.8 mm and 2 mm, respectively.

Adhesives used were the same epoxy resin with various flexibilities as those used in Section 1 (EP-0, EP-20, EP-40 and EP-60).

The process of preparation of specimens is as follows: In the first place, as shown in Fig. 10(a) wood strips with grain angle 1°–3° in the tangential section were cut from plunks and placed in a conditioned room at 20°C, 65% RH. After more than three weeks, the strips were taken out from the room, and two strips were mated so as to make converging grain (see Fig. 10(b)). Teflon sheet spacer was used to control the glue-line thickness and resin was poured into the slit to complete the reservoir type gluing[9]. After curing in a conditioned room, the specimens were finished to the size and shape

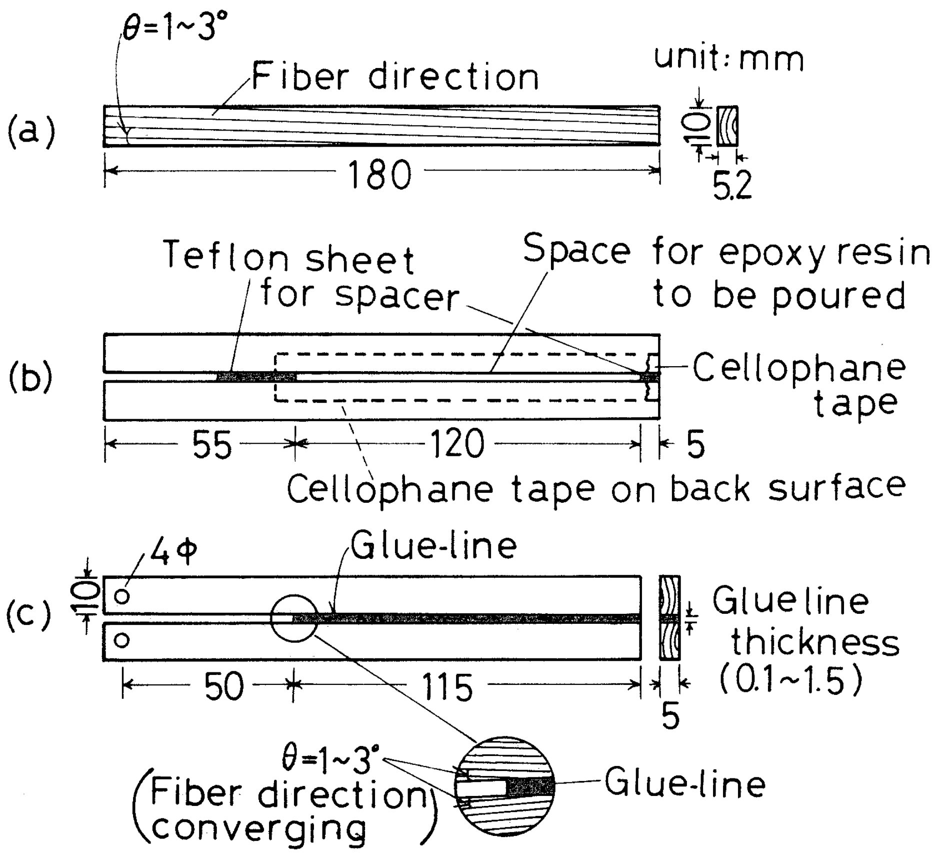


Fig. 10. Preparation of specimens for cleavage fracture toughness test.

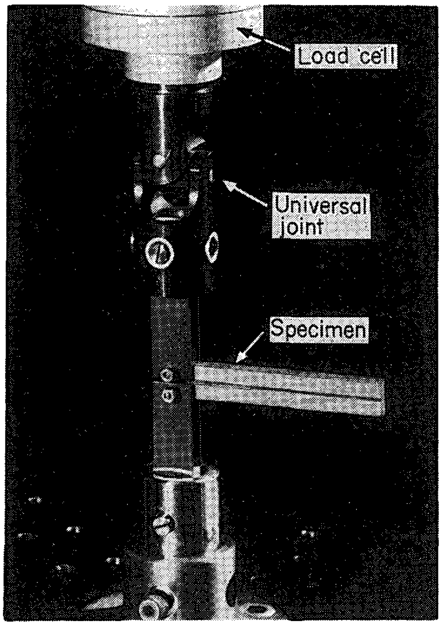


Photo. 3. Cleavage test of double cantilever type specimen.

shown in Fig. 10(c). The range of glue-line thickness was 0.1–1.5 mm.

2·2·2 *Experimental method and deriving fracture toughness*

Photo. 3 shows the loading system of cleavage test of double cantilever type specimen. Load was applied with material testing machines of Instron Model K for the test at room temperature and with Shinko TOM 5000 for the test series on temperature dependency.

Load and relative displacement between two loading points (opening) were recorded with an X-Y recorder.

Fracture toughness G_{IC} was derived from the following formula[1)]

$$G_{IC}=\frac{P_c \cdot \delta_c}{2 \cdot bh} \cdot \frac{3(\alpha+1.4)^2+\gamma}{(\alpha+1.4)^3+\alpha\gamma},$$

where, P_c and δ_c are the load and opening at which the initial fracture starts, respectively, b is the width (or thickness) of specimen, h is the height of an adherend, $\alpha=a/h$ and a is the length of unbonded part (or crack) of a specimen, and γ is a constant relating to the elastic constants of adherends (for Buna $\gamma=4$, for Taiwan hinoki $\gamma=5.4$).

2·2·3 *Results and discussion*

a) Effect of glue-line thickness and flexibility

Fracture toughness measured on Buna-epoxy resin bond system at room temperature is shown in Fig. 11. Each point in the figure is the average of ten measurements. Remarkable increase in fracture toughness is observed with increasing glue-line thickness when highly flexibilized resins (EP-60 and EP-40) are used.

For each thickness level of glue-line, clear improvement in fracture toughness is

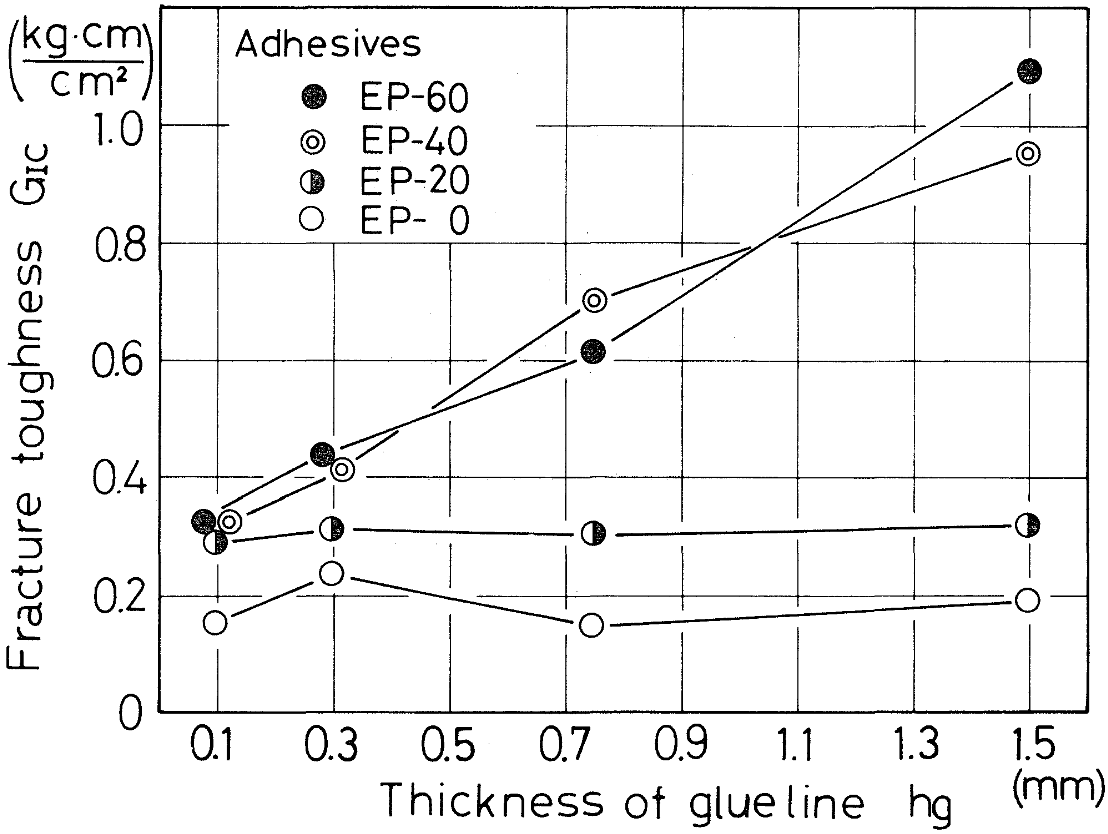


Fig. 11. Fracture toughness of buna-epoxy resin bond system as function of glue-line thickness with parameter of polysulfide content at 20°C 65% RH and test speed 1 cm/min.

made with increasing flexibility of glue-line, while there is no difference between specimens of EP-60 and EP-40.

These inclinations correspond well to the speculation from the stress analysis (Fig. 9), that is, the thicker and more flexible glue-line produces lower stress concentration at the crack tip and requires higher load and larger opening at failure which bring higher fracture toughness.

The similer effect in both specimens of EP-60 and EP-40 could be interpreted by cancelling the reduction of stress concertration in EP-60 specimen and the decrease of cohesive force of the resin.

b) Effect of temperature and test speed on fracture toughness of EP-0 specimen

Fig. 12(a)-(d) are plots of fracture toughness G_{IC} of Taiwan hinoki—Epoxy resin (EP-0, rigid resin) bond specimen as function of test speed with parameter of glue-line thickness at 30°, 40°, 50° and 60°C, respectively.

Values scattered much and effect of temperature and test speed on fracture toughness of EP-0 bond specimens is not clear. This inclinations correspond well to comparatively small variation in stress-strain curves of EP-0 film within this temperature range (refer to Fig. 6).

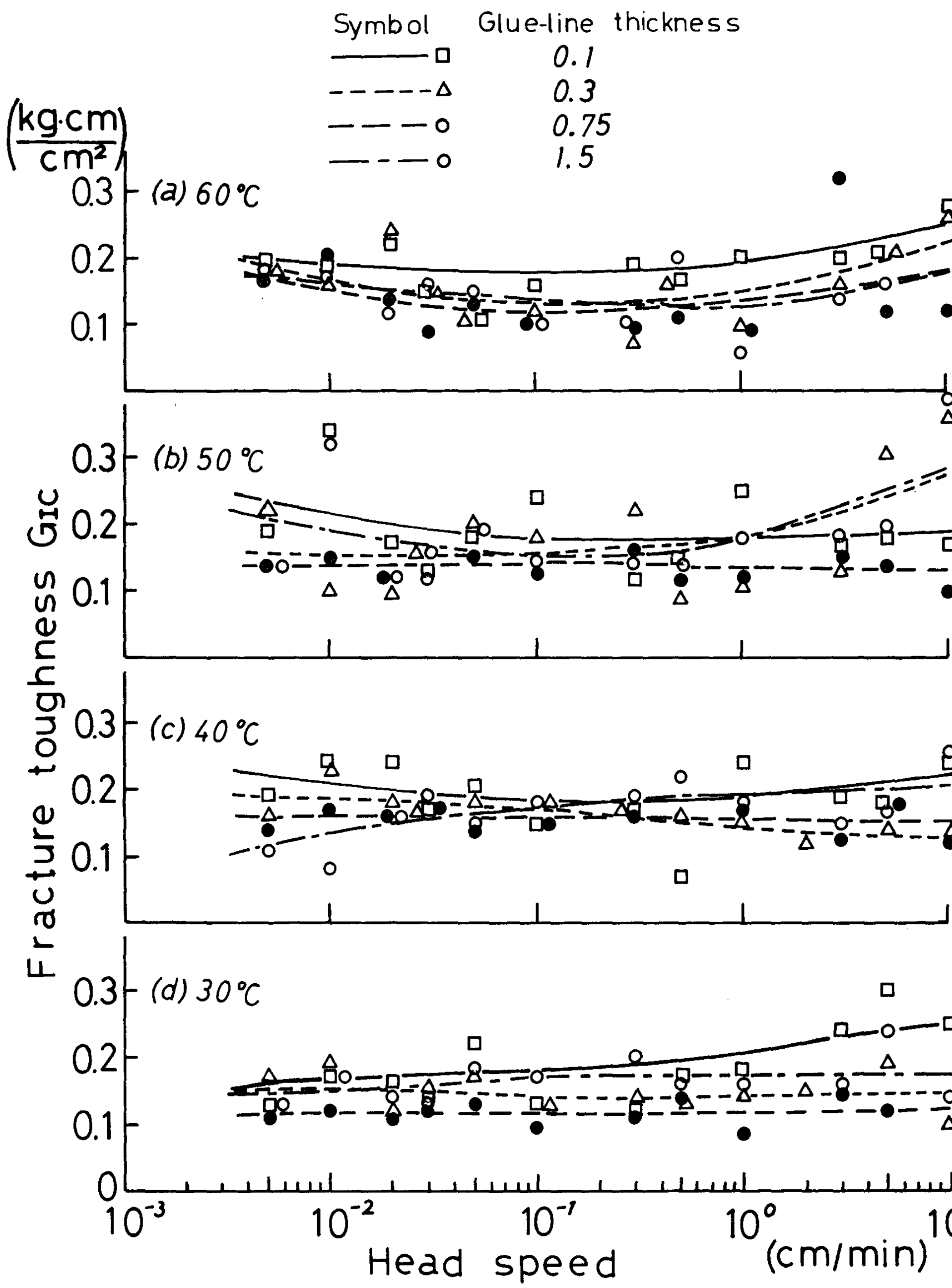


Fig. 12. Fracture toughness G_{IC} of taiwan hinoki-epoxy resin bond system (EP-0) as function of test speed with parameter of glue-line thickness (mm) and test temperature.

Table 5 shows the comparison of average fracture toughnesses obtained on each glue-line thickness and temperature. The averages are made over the head speed range from 5×10^{-3} to 10 cm/min.

In the table, fracture toughness of rigid epoxy resin (EP-0) bonded wood specimen is practically consistent at a temperature range from room temperature to 60°C for glue-line thickness ranged from 0.1 to 1.5 mm.

Table 5. Fracture toughness G_{IC} observed on Taiwan hinoki-epoxy resin bond system at different temperatures. (Average on test speed of $5 \times 10^{-3} \sim 10$ cm/min)

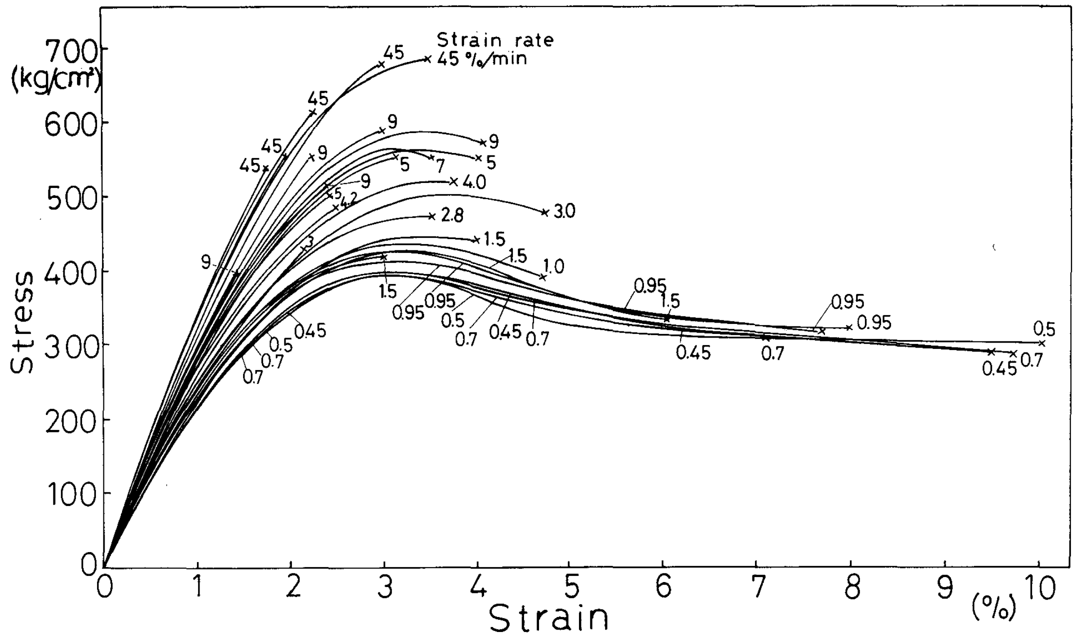
Temperature (°C)	Glue-line Thickness (mm)	Fracture toughness ($kg \cdot cm/cm^2$)	
		mean	S. D.
30	0. 1	0. 18	0. 056
	0. 3	0. 15	0. 024
	0. 75	0. 12	0. 017
	1. 5	0. 17	0. 030
		av. 0. 16	av. 0. 032
40	0. 1	0. 19	0. 079
	0. 3	0. 17	0. 028
	0. 75	0. 15	0. 020
	1. 5	0. 16	0. 039
		av. 0. 17	av. 0. 034
50	0. 1	0. 19	0. 060
	0. 3	0. 18	0. 087
	0. 75	0. 13	0. 018
	1. 5	0. 19	0. 080
		av. 0. 17	av. 0. 062
60	0. 1	0. 19	0. 042
	0. 3	0. 16	0. 056
	0. 75	0. 14	0. 065
	1. 5	0. 14	0. 041
		av. 0. 16	av. 0. 051

Conclusion

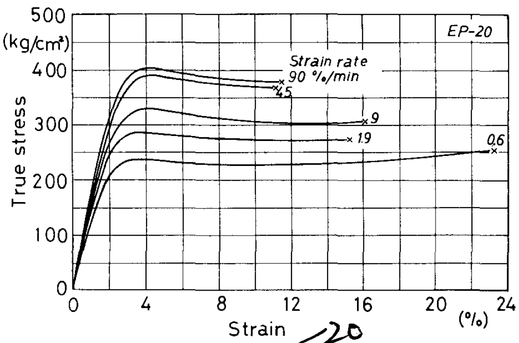
Epoxy resin is versatile in its flexibility when mixed with flexibilizer like polysulfide. The glue-line of the resin with sixty phr polysulfide (EP-60) is rubbery and can effectively reduce the stress concentration at a crack tip in the glue-line and the glue bond system will have a high fracture toughness of opening mode.

Epoxy resin without any additives (EP-0) is rigid and of high tensile strength. A crack tip in the glue-line of the resin has high stress concentration which produces low fracture toughness in cleavage of the wood-glue bond system.

In a temperature range from 20° to 60°C, flexibility of rigid resin (EP-0) does not change so much and the fracture toughness of the wood-glue bond system is almost consistent.



Supplemental fig. 1. Examples of observed stress-strain curves of EP-0 resin film specimens at room temperature.



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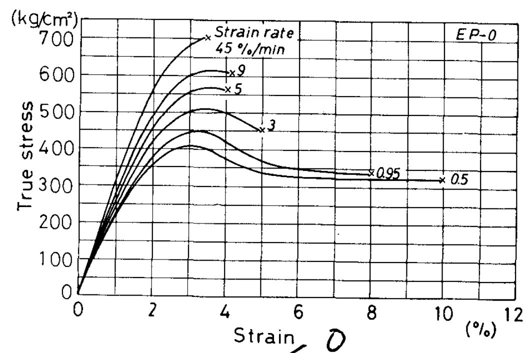
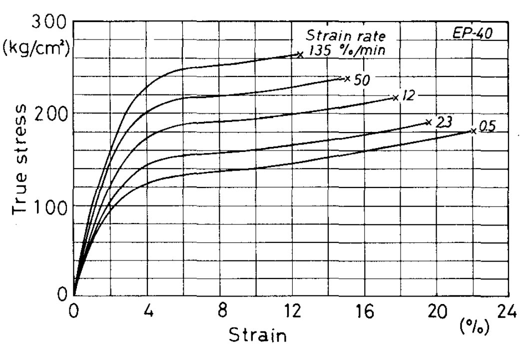
Supplemental fig. 2. Summary of stress-strain curves of EP-~~0~~ resin film specimens. Each curve is average of 3 to 7 observations. (at room temperature)

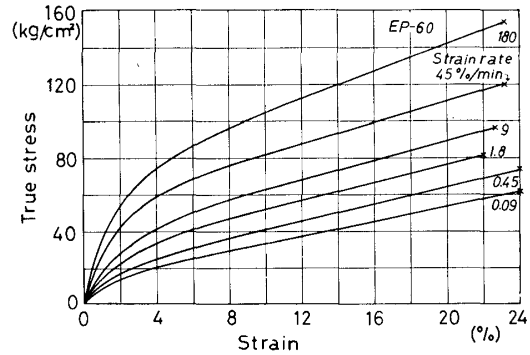


0

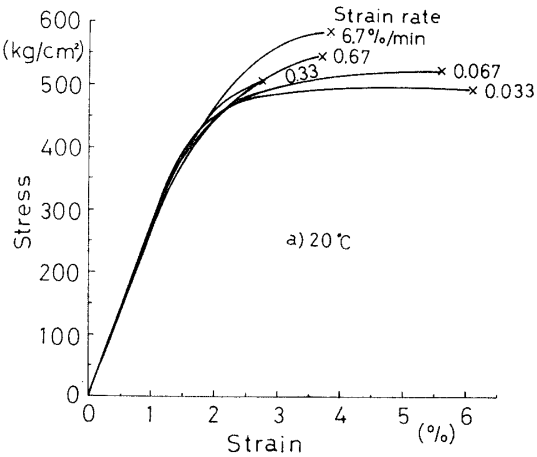
Supplemental fig. 3. Summary of stress-strain curves of EP-~~20~~ resin film specimens. Each curve is average of 3 to 7 observations. (at room temperature)



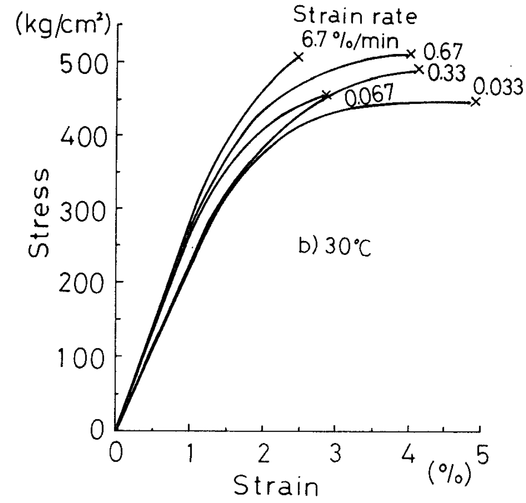
Supplemental fig. 4. Summary of stress-strain curves of EP-40 resin film specimens. Each curve is average of 3 to 7 observations. (at room temperature)



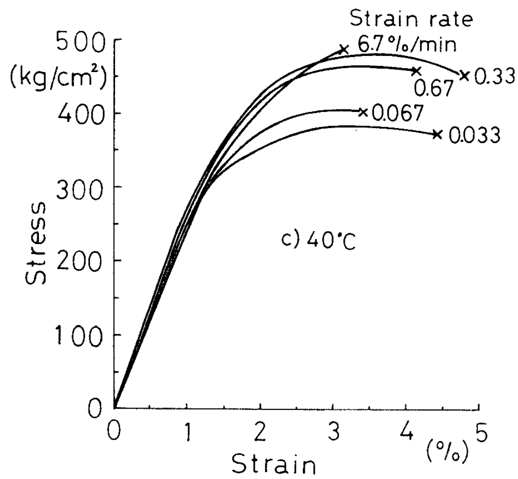
Supplemental fig. 5. Summary of stress-strain curves of EP-60 resin film specimens. Each curve is average of 3 to 7 observations. (at room temperature)



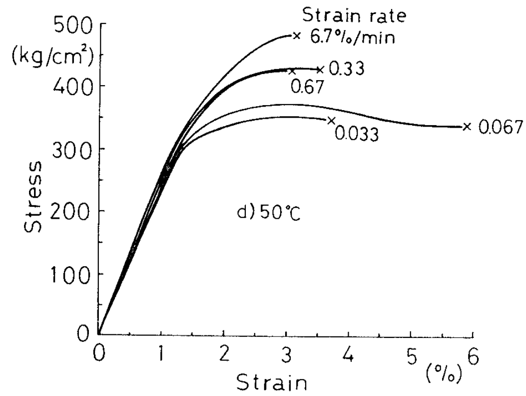
Supplemental fig. 6. Stress-strain curves of simple strip specimens of EP-0 at 20°C.



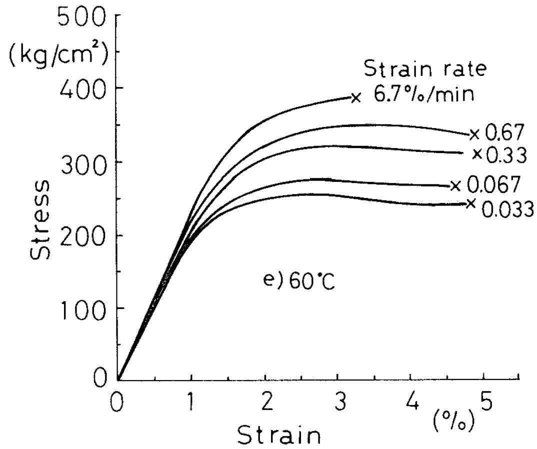
Supplemental fig. 7. Stress-strain curves of simple strip specimens of EP-0 at 30°C.



Supplemental fig. 8. Stress-strain curves of simple strip specimens of EP-0 at 40°C.



Supplemental fig. 9. Stress-strain curves of simple strip specimens of EP-0 at 50°C.



Supplemental fig. 10. Stress-strain curves of simple strip specimens of EP-0 at 60°C.

Literature

1) SASAKI, H., and P. F. WALSH, Zairyo (J. Soc. Mat. Sci., Japan) **26**, (284) 453 (1977).
2) SASAKI, H., Setchaku (Adhesion and Adhesive) **18**, 172 (1974).
3) KOMATSU, K., H. SASAKI, and T. MAKU, Wood Research (Bull. Wood Res. Inst., Kyoto Univ.) No. 61, 25 (1976).
4) KOMATSU, K., H. SASAKI, and T. MAKU, Wood Research (Bull. Wood Res. Inst., Kyoto Univ.) No. 59/60, 80 (1976).
5) SIMPSON, W. T., and V. R. SOPER, U.S.D.A., For. Serv. Res. Note, EPL-0198, (1968).
6) SIMPSON, W. T., and V. R. SOPER, U.S.D.A., For. Serv. Res. Paper, EPL126, (1970).
7) POTER, A. W., For. Prod. J., **14**, 325 (1964).
8) TAKATANI, M. and H. SASAKI, Presented at 29th Annual Meeting of Japan Wood Res. Soc. in Sapporo 1979, not printed.
9) SASAKI, H., E. MCARTHUR, and J. W. GOTTSTEIN. For. Prod. J., **23** (2), 48 (1973).
10) Forestry For. Prod. Res. Inst. (ed.), Mokuzai Kogyo Handbook, pp. 173, 174 Maruzen, Tokyo (1973).